

Available online at www.sciencedirect.com**SciVerse ScienceDirect**

Procedia Engineering 23 (2011) 608 – 615

**Procedia
Engineering**

www.elsevier.com/locate/procedia

2011 International Conference on Power Electronics and Engineering Application
(PEEA 2011)

Study of an electric vehicle drive dynamic testing system with energy recovery

Ching-Lung Chu^{a*}, Che-Wei Chou^a, Jun-Rong Chen^b, Hsiao-Yen Chan^b, Jiun-Hau Fang^b

^a Department of Electrical Engineering, Southern Taiwan University, Yongkang Dis, Tainan 710, Taiwan

^b Rich Electric Corporation Limited, Annan Dis, Tainan 709, Taiwan

Abstract

To save the test energy of the electric drive vehicle, an electric vehicle drive dynamic testing system, with energy recovery is proposed. The electric vehicle DC/AC power drive can be regulated by a speed control mode and a torque control mode in a three-phase electric vehicle induction motor. The three-phase electric vehicle induction motor is directly coupled with a three-phase load induction motor through a coupler. The load of the DC/AC power drive is also regulated by the torque control mode and the speed control mode to drive the three-phase load induction motor. The three-phase load induction motor is operated in the regenerative braking mode, and the regenerative energy of the load induction motor can be transferred to the utility system by a power regenerative DC/AC inverter that feedbacks the energy to the utility system with a unit power factor. Therefore, the proposed electric drive vehicle dynamic testing system not only achieves the dynamic test function, but saves energy.

© 2011 Published by Elsevier Ltd. Open access under [CC BY-NC-ND license](https://creativecommons.org/licenses/by-nc-nd/4.0/).

Selection and/or peer-review under responsibility of [name organizer]

Keywords: Electric vehicle drive; induction motor; power regenerative

1. Introduction

The circuit design is the element to ensure the reliable performance of the power driver and Burn-in test is also the critical testing item [1] for the electronic products such as Uninterruptable Power Supply, DC power supply, Inverter and other Power Supplies before these products are used. In general,

* Corresponding author. Tel.: +886-06-253-3131-3331; fax: +886-06-301-0073.

E-mail address: clchu@mail.stut.edu.tw.

uninterruptable power supply systems and DC power suppliers are with a constant frequency output and this has been approved by practical methods [2-3] in many papers. However, the output of the inverter is a driver with the variable voltage and variable frequency. The Burn-in test in proposed paper [4-6] can only be done in the constant output voltage and frequency but can not test the inverter with the fixed output voltage/frequency ratio.

The output feature of the electric vehicle drive is the fixed frequency/voltage ratio and once the output voltage is higher than the rated value, it becomes the constant voltage/variable frequency output. This design of an energy saving test electric vehicle drive system that will have both burn-in and dynamic feature. An electric vehicle drive dynamic testing system with energy recovery is proposed in this paper. After testing the basic circuit and the performance of the electric vehicle drive, the drive should run the three-phase induction motor with the rated power and increase the three-phase induction motor load capacity from the light load to full load. In order to have the test system achieve the purpose of dynamic resonance and energy saving, the control mode of the electric vehicle driver operates in the two testing mode. (A) The three-phase electric vehicle induction motor is operated at the speed control mode; the speed direction of the electric vehicle induction motor is the same as the torque direction. The battery energy is supplied to the DC/AC inverter to drive the three-phase electric vehicle induction motor. The load of the electric vehicle induction motor still adopt the induction motor that is called load induction motor that is coupled directly with the three-phase electric vehicle induction motor through the coupler. Meanwhile, the three-phase load motor runs in the torque control mode, the speed direction and the torque direction of the load motor are reversed. (B) The three-phase vehicle induction motor is operated at the torque control mode; the speed direction is the same as the torque direction. The battery energy is supplied to the DC/AC inverter to drive the three-phase electric vehicle induction motor. The three-phase induction motor load is operated at the speed control mode. The speed direction is the same as the torque direction. The energy of the three-phase electric vehicle induction motor is absorbed by the DC capacitors of the driver of the three-phase induction motor load. The power regenerative DC/AC inverter is operated with a unit power factor to feedback the energy to the utility system and this achieves the purpose of dynamic load testing and energy saving.

2. Configuration of the proposed test System

The system prototype structure of testing on the electric vehicle drive that can feedback the energy is shown in the Fig 1 and the testing analysis of the drive energy saving is divided into three sections. 2.1 the basic regenerative braking operation of the three-phase induction motor, 2.2 Three-phase electric vehicle induction motor drive, 2.3 Three-phase load induction motor drive and the three sections are introduced respectively.

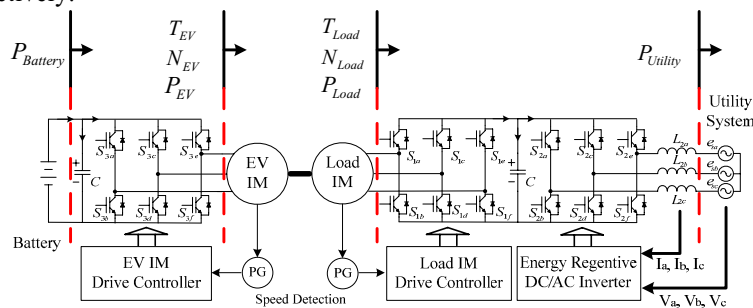


Fig. 1. Configuration of the electric vehicle drive dynamic testing system with energy recovery

2.1. Regenerative braking operation of three-phase induction motor

The basic four-quadrant operation of the three-phase induction motor is shown in Fig 2(a). ω_s is the magnetic rotation of the induction motor stator, ω_M is the rotor speed of the induction motor, T_M is the torque output direction of the three-phase induction motor and T_L is the output direction of load torque. The first and third quadrant is the motor operation mode and the second and fourth quadrant is the regenerative braking operation mode [1]. The operation relation between the output torque T_M and the rotor speed ω_M of the three-phase induction motor is shown in the Fig 2(b). When $\omega_s > \omega_M$, the three-phase induction motor operates in motor operation mode which falls in the first and third quadrant. When $\omega_s < \omega_M$, the three-phase induction motor operates in regenerative braking operation mode which falls in the second and fourth quadrant. The design of the three-phase induction motor drive is featured with the maximum slip S ($S = \frac{\omega_s - \omega_M}{\omega_s}$) limit, maximum rated input current limit and maximum rated rotor speed limit to ensure that the three-phase induction motor is able to operate in the stable negative slope (output torque T_M and rotor speed ω_M).

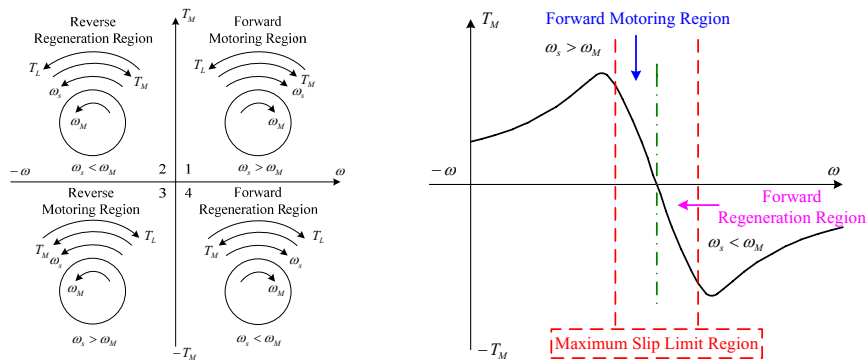


Fig. 2. (a) Basic four-quadrant operations of three-phase induction motor; (b) operation relation of output torque T_M and rotor speed ω_M of three-phase induction motor

2.2. Three- phase electric Vehicle Induction Motor Driver

The basic structure of the three-phase electric vehicle induction motor is shown in Fig 3(a). The electric vehicle motor is 3-phase, Y-connection type 220V 40kW induction motor and the battery voltage of the electric vehicle is 360~420V. The auxiliary battery voltage is 24V and it is supplied by the isolated DC/DC converter for the low-voltage power to start the electric vehicle. Once the electric vehicle is turned on, auxiliary power is on, the resistor R of the battery soft charge the capacitor C of the DC voltage to reduce the rush current. When the DC voltage V_{dc} increases to the preset value, the driving control circuit will output the control signal to turn the main relay for the completion of the IGBT driving power and all the power of the electric vehicle is finished now. Finally, drivers can drive the electric vehicle on the car control pedal.

The magnetic torque that the three-phase induction motor generates is the direct proportion to the multiplication of the rotor flux and d axis stator current. The key to control the torque amount is to keep the rotor flux as a fixed value and control the current of d axis stator current. The rotor flux and d axis

stator current can be controlled individually just as the DC brushed motor control. The basic structure of the field-oriented control in the vehicle induction motor driver is shown in Fig 3(b).

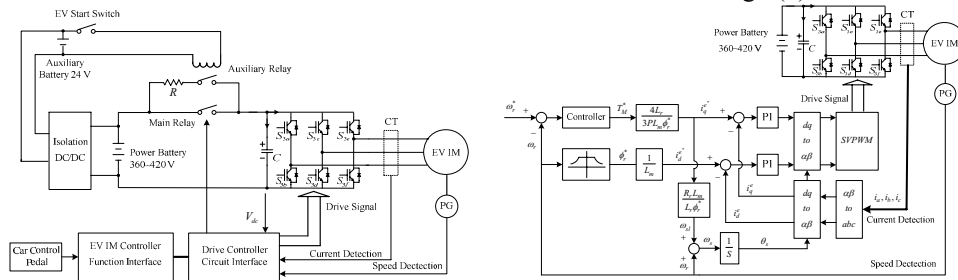


Fig. 3. (a) Electric vehicle induction motor driver; (b) field-oriented control in the vehicle induction motor drive

2.3. Three-phase load induction motor drive

The basic structure of the three-phase load induction motor is same as electric vehicle induction motor and the DC voltage is supplied by the converter with power feedback function. The DC voltage is 400V. The control structure of the other parts is the same as the vehicle induction motor driver and the controller is set for the constant torque or speed control.

3. Power regenerative DC/AC inverter

When the three-phase induction motor driver operates in the regenerative braking mode (the second quadrant), three-phase induction motor is regarded as three-phase generator. This three-phase induction generator generates the energy to feedback to the DC source with the help of the drive. The DC source receives the regenerative energy and the DC capacitor voltage rises and stores the energy. The DC/AC inverter with energy feedback function in this energy saving system can regenerate the energy and feedback it to the AC grid and reduce the AC grid harmonics. The power regenerative DC/AC inverter with energy feedback commonly uses the current control and the current control is divided into three-phase AC individual current control, two-axis AC current control of the transfer of the $\alpha\beta$ axis and the DC current control of the transfer of dq axis[7-10]. The transistor driving has SPWM and SVPWM [11-13]. Fig 4(a) shows the individual current control of each phase, Fig 4(b) shows the block diagram of the two-axis AC current control of the $\alpha\beta$ axis transfer. Fig 4(c) shows the block diagram of the DC current control of the dq axis transfer.

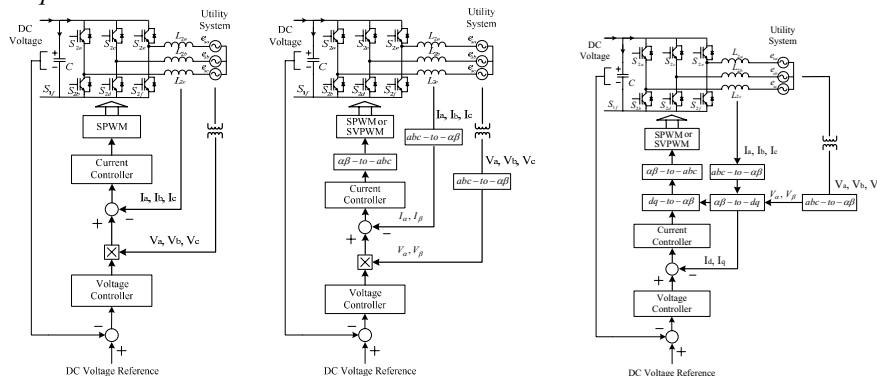


Fig. 4. (a) Individual current control of each phase; (b) current control with $\alpha\beta$ axis transfer; (c) current control with dq axis transfer

4. Analysis of the electric drive vehicle dynamic energy save testing system

Fig 1 shows the overall system connection after the completion of the individual test of the three-phase vehicle induction motor driver, three-phase load induction motor driver and the converter with energy feedback function. First, switch on the converter with energy feedback function and input the voltage of three-phase AC 220V/60Hz grid power, set the DC voltage to be 400V and then switch on the three-phase induction motor driver (the battery voltage range is 360~420V) and the three-phase load induction motor driver. According to the operation mode of the three-phase load induction motor, there are two energy saving methods: (A) When the operation mode of the three-phase electric vehicle induction motor drive is set as the speed control, the three-phase load induction motor driver must be set as the torque control and the torque direction is in counter direction to the speed direction of electric vehicle induction motor. (B) When the operation mode of the three-phase electric vehicle induction motor drive is set as the torque control, the three-phase load induction motor driver must be set as the speed control and the speed direction is in counter direction to the torque direction of the electric vehicle induction motor. The following sections further illustrates the two testing types for energy saving.

4.1. Operation mode of the three-phase electric vehicle induction motor drive set as speed control

When the operation mode of the three-phase electric vehicle induction motor drive is set as the speed control, the 3-phase load induction motor driver must be set as the torque control and the torque direction is in counter direction to the speed direction of electric vehicle induction motor. Fig 5(a) shows the torque and speed operation direction when the mechanical connection axes are directly coupled in the condition of three-phase electric vehicle induction motor driver being set as speed control mode and the three-phase load induction motor driver being set as torque control mode. The parameters that are output from the three-phase induction motor is stator rotation magnetic speed ω_{s-EV} , rotor speed ω_{r-EV} , torque output direction T_{M-EV} and load torque direction T_{L-EV} . When the three-phase electric vehicle induction motor operates in the motor mode, the energy is supplied by the battery. When the three-phase load induction motor driver is set as torque control, the motor controlled by it outputs the parameters of stator rotation magnetic speed ω_{s-LOAD} , rotor speed ω_{r-LOAD} , torque output direction T_{M-LOAD} and load torque direction T_{L-LOAD} . In this energy saving test system, the three-phase electric vehicle induction motor is directly coupled with the three-phase load induction motor so the rotor direction and the speed of the three-phase vehicle induction motor is the same as the three-phase load induction motor; namely, $\omega_{r-LOAD} = \omega_{r-EV}$. In the steady $\omega_{s-LOAD} < \omega_{s-EV}$, the three-phase load induction motor operates in the regenerative braking mode and the regenerative torque of the three-phase load induction motor is equal to the output torque of the three-phase vehicle induction motor; namely, $T_{M-LOAD} = T_{L-EV}$ and $T_{L-LOAD} = T_{M-EV}$. Fig 5(b) shows the steady of torque and speed when the operation mode of the three-phase electric vehicle induction motor drive is set as speed control and the operation mode of the three-phase load induction motor is set as torque control. Therefore, controlling the torque of the three-phase load induction motor driver could mean the three-phase load induction motor is regarded as the output load of the three-phase vehicle induction motor. The output load can regenerate the energy and the converter feedbacks the energy to the AC grid so the power consumption of the test is merely the loss of the driver and induction motor.

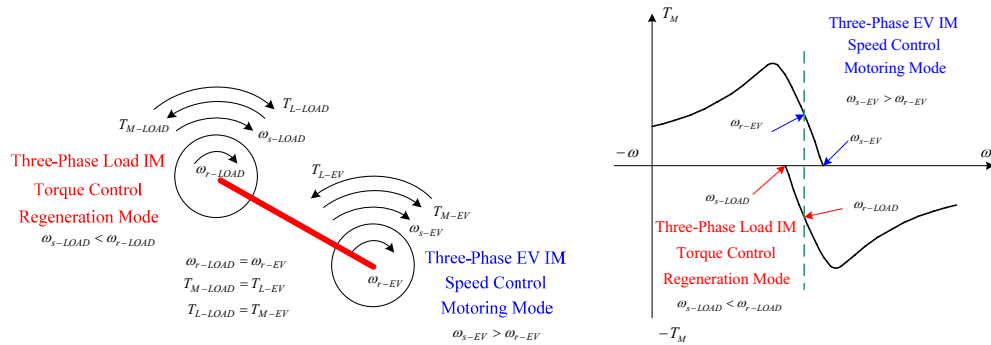


Fig. 5. (a) Torque and Speed operation direction of the three-phase electric vehicle induction motor (speed control) and load induction motor (torque control); (b) steady torque and speed of three-phase electric vehicle induction motor (speed control) and load induction motor (torque control)

4.2. Operation mode of the three-phase electric vehicle induction motor drive set as torque control

When the operation mode of the three-phase electric vehicle induction motor driver is set as the torque control, the 3-phase load induction motor driver must be set as the speed control and the speed direction is in the same direction as the torque direction of electric vehicle induction motor. Fig 6(a) shows the torque and speed direction when the mechanical connection axes are directly coupled in the condition of three-phase electric vehicle induction motor drive being set as torque control mode and the three-phase load induction motor driver being set as speed control mode. Fig 6(b) shows the steady of torque and speed when the operation mode of the three-phase electric vehicle induction motor driver is set as speed control and the operation mode of the three-phase load induction motor is set as torque control. The control patterns of the three-phase electric vehicle induction motor driver and the three-phase load induction motor driver are similar to those illustrated in 4.1 section so the object of energy saving is accomplished.

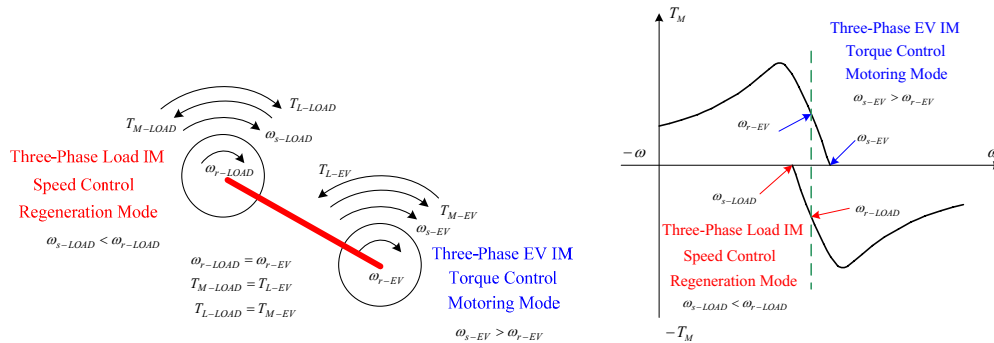


Fig. 6. (a) Torque and speed operation direction of three-phase induction motor (torque control) and load induction motor (speed control); (b) steady torque and speed of three-phase electric vehicle induction motor (torque control) and load induction motor (speed control)

5. Experimental results of the drive energy save testing system

The prototype of the electric vehicle drive dynamic testing system with energy recovery is shown in Fig. 1. The battery voltage range is 360~420V and the output of the three-phase electric vehicle induction motor driver is 220V 40kW. The electric vehicle induction motor is three phase, Y connection, 220V 40kW. Three-phase load induction motor is also three phase, Y connection, 220V 40kW. The output of the three-phase load induction motor driver is 220V 40kW and the AC grid power is three phase 220V/60Hz.

Fig 7 (a) is the output waveform of the three-phase electric vehicle induction motor driver when the three-phase electric vehicle induction motor drive operates in the speed control mode. Fig 7 (b) is the output waveform of the three-phase load induction. Fig 7 (c) is the waveform of the converter with energy feedback function.

Table 1. Variation values of speed, torque and power in the speed control mode.

P_{Battery} (kW)	N_{EV} (rpm)	T_{EV} (kg-m)	P_{EV} (kW)	T_{Load} (kg-m)	P_{Load} (kW)	P_{Utility} (kW)	$\eta = \frac{P_{\text{Utility}}}{P_{\text{Battery}}}$
4.4	200	21.6	3.96	21.6	3.4	3	0.68182
8.9	400	21	7.92	21	6.8	6	0.67416
12.9	600	20.3	11.2	20.3	9.4	8.4	0.65116
18.8	800	21.6	16.5	21.6	14.1	12.5	0.66489
23.2	1000	21.5	20.8	21.5	17.9	15.9	0.68534
27	1200	20.3	24.3	20.3	20.9	18.6	0.68889
32.6	1400	20.5	28.3	20.5	24.67	21.8	0.66871
36.6	1600	21.3	32.2	21.3	28.2	24.9	0.68033
39.3	1800	22.1	34.5	22.1	30.1	26.6	0.67684

Table 2. Variation values of speed, torque and power in the torque control mode.

P_{Battery} (kW)	N_{EV} (rpm)	T_{EV} (kg-m)	P_{EV} (kW)	T_{Load} (kg-m)	P_{Load} (kW)	P_{Utility} (kW)	$\eta = \frac{P_{\text{Utility}}}{P_{\text{Battery}}}$
4.2	200	20.1	3.7	20.1	3.3	2.7	0.63360
8.7	400	21.2	7.7	21.2	6.7	5.7	0.65076
13.2	600	22.3	11.6	22.3	10.2	9.1	0.68922
19.5	800	21.6	17.2	21.6	15.3	12.2	0.62656
22.6	1000	22.2	19.9	22.2	17.9	15.4	0.68112
28.1	1200	23.1	24.7	23.1	21.8	18.9	0.67373
34.1	1400	22.2	30.0	22.2	27.0	24.0	0.70488
37.2	1600	22.5	32.7	22.5	29.5	26.2	0.70488
39.1	1800	23.3	34.4	23.3	31.0	27.6	0.70488

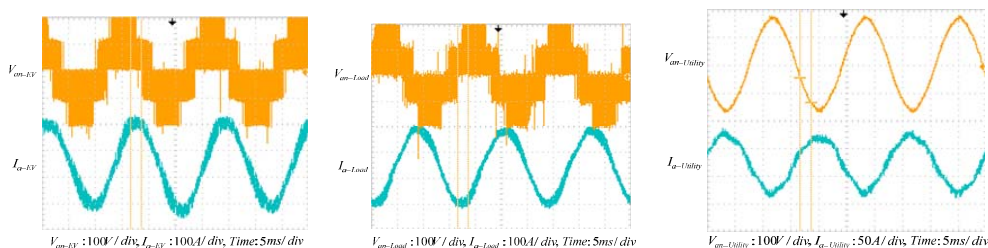


Fig. 7. Operation mode of the three-phase electric vehicle induction motor driver set as speed control; (a) output waveform of the electric vehicle induction motor drive; (b) output waveform of the load induction motor driver; (c) output waveform of the power regenerative DC/AC inverter.

6. Conclusions

The proposed electric vehicle drive dynamic testing system with energy recovery has the DC/AC inverter selectable for the speed control or torque control to drive the three-phase electric vehicle induction motor. The three-phase electric vehicle induction motor can be controlled from the light load to the full load to accomplish the dynamic test. The power of the three-phase electric vehicle induction motor comes from the coupling with the three-phase load induction motor. The DC/AC inverter drives the three-phase load induction motor with the torque control and constant speed control and this three-phase load induction motor operates in regenerative braking mode to further feedback the power to the utility system through the power regenerative DC/AC inverter with a unit power factor low harmonics sine wave. As a result of this test, the electric vehicle drive dynamic testing system simulates the full-range speed and torque output to save 65~70% energy.

Acknowledgements

Thanks to the joint cooperation with Rich Electric for the study project: 120990065, the research effort and the fund is much appreciated.

References

- [1] P. Vas, *Vector Control of AC Machines*, Clarendon Press Oxford, 1990.
- [2] E. A. Vendrusculo, J. A. Pomilio, "High-Efficiency Regenerative Electronic Load using Capacitive Idling Converter for Power Source Testing," IEEE PESC, pp. 969-974, 1996.
- [3] C. A. Ayres, I. Barbi, "A Family of Converter for UPS Production Burn-in Energy Recovery," IEEE Trans. on Power Electronics, Vol. 12, No. 4, pp. 615-622, 1997.
- [4] D. H. Braun, T. P. Gilmore, W. A. Maslowski, "Regenerative converter for PWM AC drives," IEEE Transactions on Industry Applications, Vol. 30, No. 5, pp. 1176-1184 September/October 1994
- [5] H. Inaba, K. Hirasawa, T. Ando, M. Hombu, M. Nakazato, "Development of a high-speed elevator controlled by current source inverter system with sinusoidal input and output," IEEE Trans. Industry Applications, Vol. 28, No. 4, pp. 893-899, July 1992.
- [6] S. Saha, T. Kosaka, N. Matsui, V. P. Sundarsingh, "Regenerative braking in a low power lift drive system," IEEE PEDES, Vol. 2, pp. 827-832, December 1998.
- [7] M. P. Kazmierkowski, M. A. Dzieniakowski, W. Sulkowski, "Novel space vector based current controllers for PWM-inverters," IEEE Trans. on Power Electronics, Vol. 6, No. 1, pp. 158-166, January 1991.
- [8] A. Nabae, S. Ogasawara, H. Akagi, "A novel control scheme for current-controlled PWM inverters," IEEE Trans. on Industry Applications, Vol. 22, No. 4, pp. 697-701, July/August 1986.
- [9] Y. Yang, M. Kazerani, "Modeling, Control and Implementation of Three-Phase PWM Converters," IEEE Trans. on Power Electronics, Vol. 18, No. 3, pp. 857-864, May 2003.
- [10] M. P. Kazmierkowski, L. Malesani, 24. "Current Control Techniques for Three-Phase Voltage-Source PWM Converters: A Survey," IEEE Trans. on Industry Electronics, Vol. 45, No.5, pp. 691-703, October 1998.
- [11] D. C. Lee, G. M. Lee, "A Novel Over-modulation Technique for Space-Vector PWM Inverter," IEEE Trans. Power Electronics, Vol. 13, No. 6, pp. 1144-1151, November 1988.
- [12] A. M. Trzynadlowski, "An Overview of Module PWM Techniques for Three-Phase Voltage-Controlled Voltage-Source Inverter," IEEE ISIE, Vol. 1, pp. 25-39, 1996.
- [13] Y. Tzou and H. J. Hus, "FPGA Realization of Space-Vector PWM Control IC for Three-Phase PWM Inverters," IEEE Trans. on Power Electronics, Vol. 12, No. 6, pp. 953-963, November 1997.